Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Grays Harbor NWR

U. S. Fish and Wildlife Service
National Wildlife Refuge System
Division of Natural Resources and Conservation Planning
Conservation Biology Program
4401 N. Fairfax Drive - MS 670
Arlington, VA 22203

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warren pinnacle consulting, inc.

Warren Pinnacle Consulting, Inc.
PO Box 315, Waitsfield VT, 05673
(802) 496-3476

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea-level rise (SLR). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) suggested that global sea level will increase by approximately 30 cm to 100 cm by 2100 (IPCC 2001). Rahmstorf (2007) suggests that this range may be too conservative and that the feasible range by 2100 is 50 to 140 cm. Rising sea levels may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat "migration" as salt marshes transgress landward and replace tidal freshwater and irregularly-flooded marsh (Park et al. 1991).

In an effort to address the potential effects of sea level rise on United States national wildlife refuges, the U. S. Fish and Wildlife Service contracted the application of the SLAMM model for many coastal refuges. This analysis is designed to assist in the production of comprehensive conservation plans (CCPs) for each refuge along with other long-term management plans. This analysis is a summary of model runs produced by Ducks Unlimited (Warren Pinnacle Consulting, Inc. 2010).

Model Summary

Changes in tidal marsh area and habitat type in response to sea-level rise were modeled using the Sea Level Affecting Marshes Model (SLAMM 6) that accounts for the dominant processes involved in wetland conversion and shoreline modifications during long-term sea level rise (Park et al. 1989; www.warrenpinnacle.com/prof/SLAMM).

Successive versions of the model have been used to estimate the impacts of sea level rise on the coasts of the U.S. (Titus et al. 1991; Lee et al. 1992; Park et al. 1993; Galbraith et al. 2002; National Wildlife Federation & Florida Wildlife Federation 2006; Glick et al. 2007; Craft et al. 2009). The first phase of this work was completed using SLAMM 5, while the second phase simulations were run with SLAMM 6.

Within SLAMM, there are five primary processes that affect wetland fate under different scenarios of sea-level rise:

- **Inundation:** The rise of water levels and the salt boundary are tracked by reducing elevations of each cell as sea levels rise, thus keeping mean tide level (MTL) constant at zero. The effects on each cell are calculated based on the minimum elevation and slope of that cell.
- **Erosion:** Erosion is triggered based on a threshold of maximum fetch and the proximity of the marsh to estuarine water or open ocean. When these conditions are met, horizontal erosion occurs at a rate based on site-specific data.
- **Overwash:** Barrier islands of under 500 meters width are assumed to undergo overwash during each specified interval for large storms. Beach migration and transport of sediments are calculated.

- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the fresh water table to rising sea level close to the coast.
- **Accretion:** Sea level rise is offset by sedimentation and vertical accretion using average or site-specific values for each wetland category. Accretion rates may be spatially variable within a given model domain and can be specified to respond to feedbacks such as frequency of flooding.

SLAMM Version 6.0 was developed in 2008/2009 and is based on SLAMM 5. SLAMM 6.0 provides backwards compatibility to SLAMM 5, that is, SLAMM 5 results can be replicated in SLAMM 6. However, SLAMM 6 also provides several optional capabilities.

- Accretion Feedback Component: Feedbacks based on wetland elevation, distance to channel, and salinity may be specified. This feedback will be used in USFWS simulations, but only where adequate data exist for parameterization.
- Salinity Model: Multiple time-variable freshwater flows may be specified. Salinity is estimated and mapped at MLLW, MHHW, and MTL. Habitat switching may be specified as a function of salinity. This optional sub-model is not utilized in USFWS simulations.
- Integrated Elevation Analysis: SLAMM will summarize site-specific categorized elevation ranges for wetlands as derived from LiDAR data or other high-resolution data sets. This functionality is used in USFWS simulations to test the SLAMM conceptual model at each site. The causes of any discrepancies are then tracked down and reported on within the model application report.
- Flexible Elevation Ranges for land categories: If site-specific data indicate that wetland elevation ranges are outside of SLAMM defaults, a different range may be specified within the interface. In USFWS simulations, the use of values outside of SLAMM defaults is rarely utilized. If such a change is made, the change and the reason for it are fully documented within the model application reports.
- Many other graphic user interface and memory management improvements are also part of the new version including an updated *Technical Documentation*, and context sensitive help files.

For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 6.0 *Technical Documentation* (Clough et al. 2010). This document is available at http://warrenpinnacle.com/prof/SLAMM

All model results are subject to uncertainty due to limitations in input data, incomplete knowledge about factors that control the behavior of the system being modeled, and simplifications of the system (CREM, 2008). Site-specific factors that increase or decrease model uncertainty may be covered in the *Discussion* section of this report.

Sea Level Rise Scenarios

Forecast simulations used scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 family of scenarios assumes that the future world includes rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. In particular, the A1B scenario assumes that energy sources will be balanced across all sources. Under the A1B scenario, the IPCC WGI Fourth Assessment Report (IPCC 2007) suggests a likely range of 0.21 to 0.48 meters of sea level rise by 2090-2099 "excluding future rapid dynamical changes in ice flow." The A1B-mean scenario that was run as a part of this project falls near the middle of this estimated range, predicting 0.39 meters of global sea level rise by 2100. A1B-maximum predicts 0.69 meters of global SLR by 2100.

The latest literature (Chen et al. 2006; Monaghan et al. 2006) indicates that the eustatic rise in sea levels is progressing more rapidly than was previously assumed, perhaps due to the dynamic changes in ice flow omitted within the IPCC report's calculations. A recent paper in the journal *Science* (Rahmstorf 2007) suggests that, taking into account possible model error, a feasible range by 2100 of 50 to 140 cm. This work was recently updated and the ranges were increased to 75 to 190 cm (Vermeer and Rahmstorf 2009). Pfeffer et al. (2008) suggests that 2 meters by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. A recent US intergovernmental report states "Although no ice-sheet model is currently capable of capturing the glacier speedups in Antarctica or Greenland that have been observed over the last decade, including these processes in models will very likely show that IPCC AR4 projected sea level rises for the end of the 21st century are too low." (Clark 2009) A recent paper by Grinsted et al. (2009) states that "sea level 2090-2099 is projected to be 0.9 to 1.3 m for the A1B scenario…" Grinsted also states that there is a "low probability" that SLR will match the lower IPCC estimates.

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 meter, 1½ meters, and 2 meters of eustatic sea-level rise by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 1).

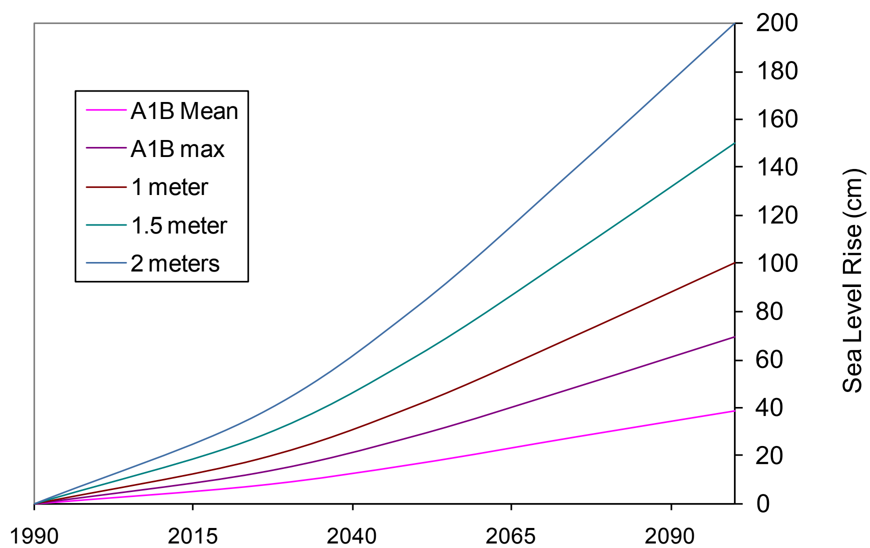


Figure 1: **Summary of SLR scenarios utilized**

Methods and Data Sources

The digital elevation map (DEM) used in this model simulation was derived from a combination of LiDAR and the USGS National Elevation Dataset (NED), Figure 2. The LiDAR was produced by the Puget Sound LiDAR Consortium in 2002, and was available as 6 foot cells. The USGS NED data ranges from the early 1950s and the early 1980s, with contour intervals of either 20 or 40 feet. LiDAR coverage did not include Grays Harbor NWR, therefore the elevation pre-processor module of SLAMM was employed (Clough et al. 2010).

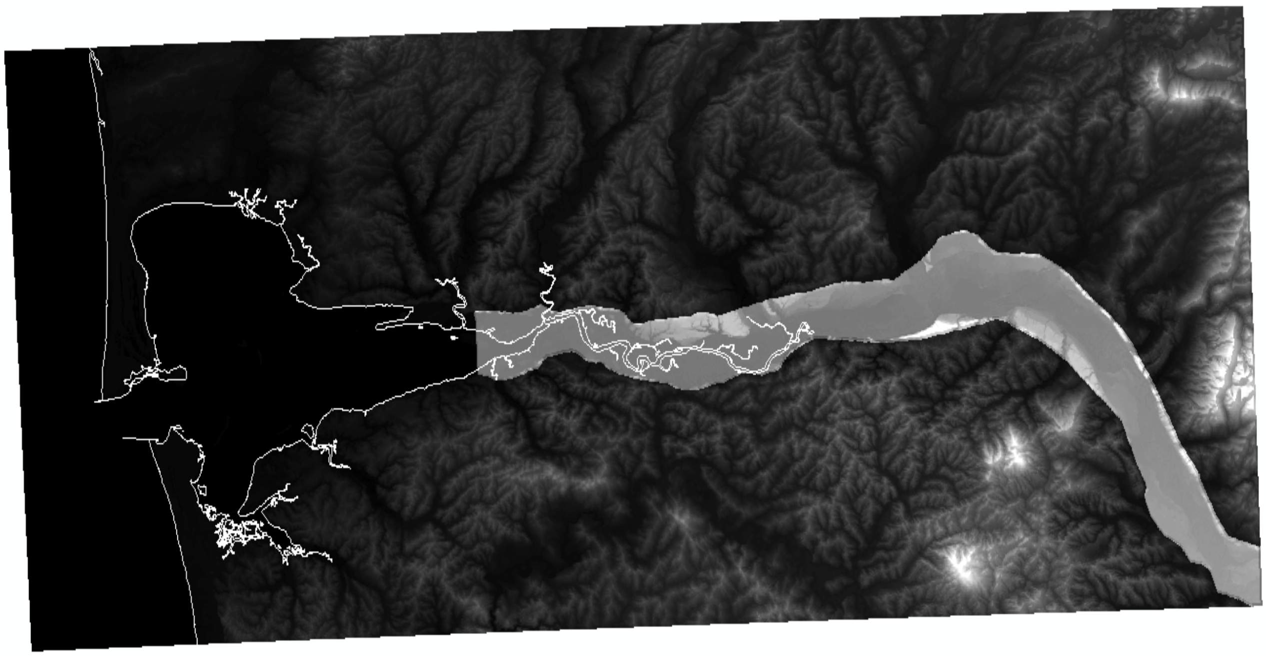


Figure 2: Extent of LiDAR elevation datasets (light gray). The remainder is composed of USGS NED.

Land-cover categories within the modeling for Grays Harbor were derived from the National Wetlands Inventory (NWI). The NWI coverage for Grays Harbor was based on 1981 photography. Converting the NWI survey into 15 m cells indicated that the approximately 1,850 acre refuge (approved acquisition boundary including water) is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Tidal Flat	1210	65
	Estuarine Open Water	375	20
	Regularly Flooded Marsh	87	5
	Undeveloped Dry Land	67	4
	Irregularly Flooded Marsh	49	3
	Estuarine Beach	23	1
	Tidal Fresh Marsh	19	1
	Inland Fresh Marsh	12	1
	Developed Dry Land	5	< 1
	Tidal Swamp	2	< 1
	Total (incl. water)	**1849**	**100**

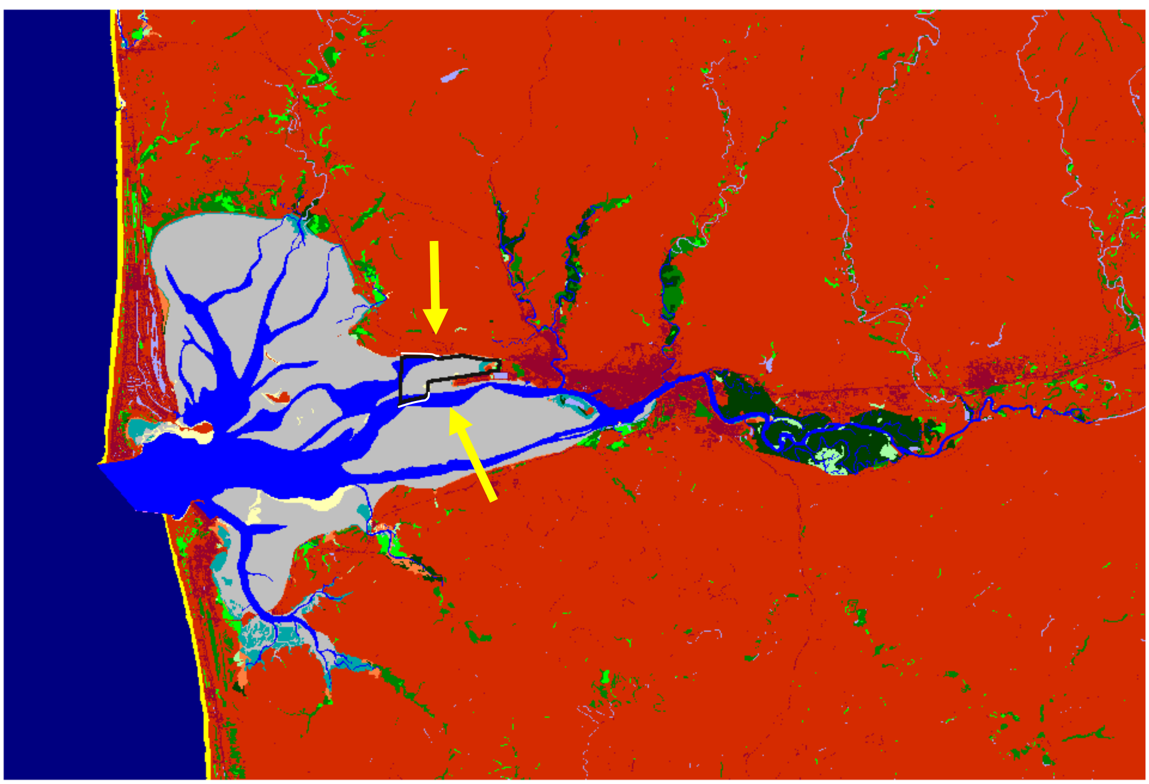


Figure 3. Study area for Grays Harbor NWR. Black line indicates Refuge boundary

The tide range for Grays Harbor was applied in a spatially variable manner using several NOAA tide gauges (see Figure 4) (9441156, Point Brown, WA; 9441102, Westport, WA; 9441187, Aberdeen, WA). As shown in Table 1, tides range between 2.8 m to 3.1 m. To reflect these tidal variations, the study area was split into different simulation input regions, as shown in Figure 6.

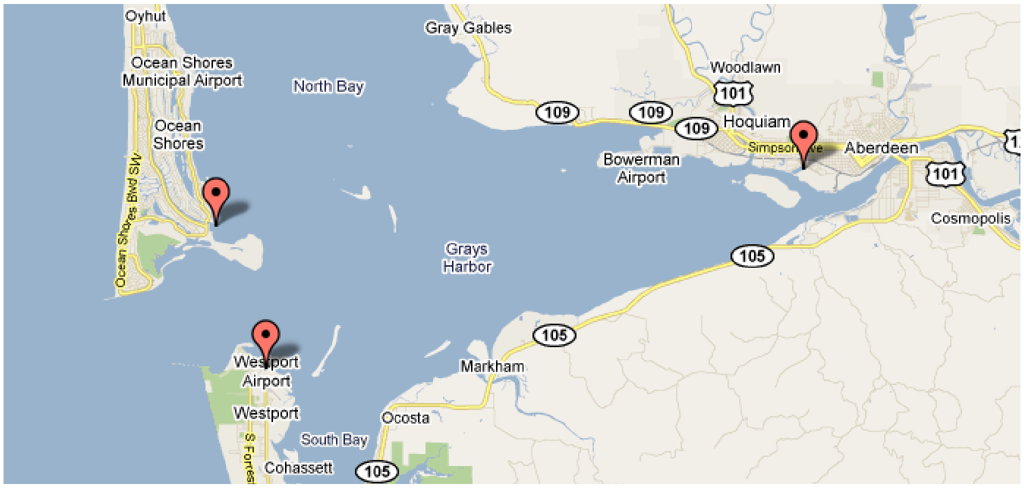


Figure 4: NOAA Gauges Relevant to the Study Area.

The "Mean High Water Spring" parameter within SLAMM designates the salt boundary -- the boundary between wet lands and dry lands or saline wetlands and fresh water wetlands. As such, this value may be best derived by examining historical tide gage data (9441187, Aberdeen, WA). For this application, the salt boundary was defined as the elevation above which inundation is predicted less than once per thirty days. Based on this analysis (Figure 5) the global SLAMM mean high water spring (MHWS) was globally set to 1.99 meters or 140% of MHHW (relative to MTL). Lands above this elevation are assumed to be free of saline influence for the most part (e.g. dry lands, inland fresh marsh, and swamps.)

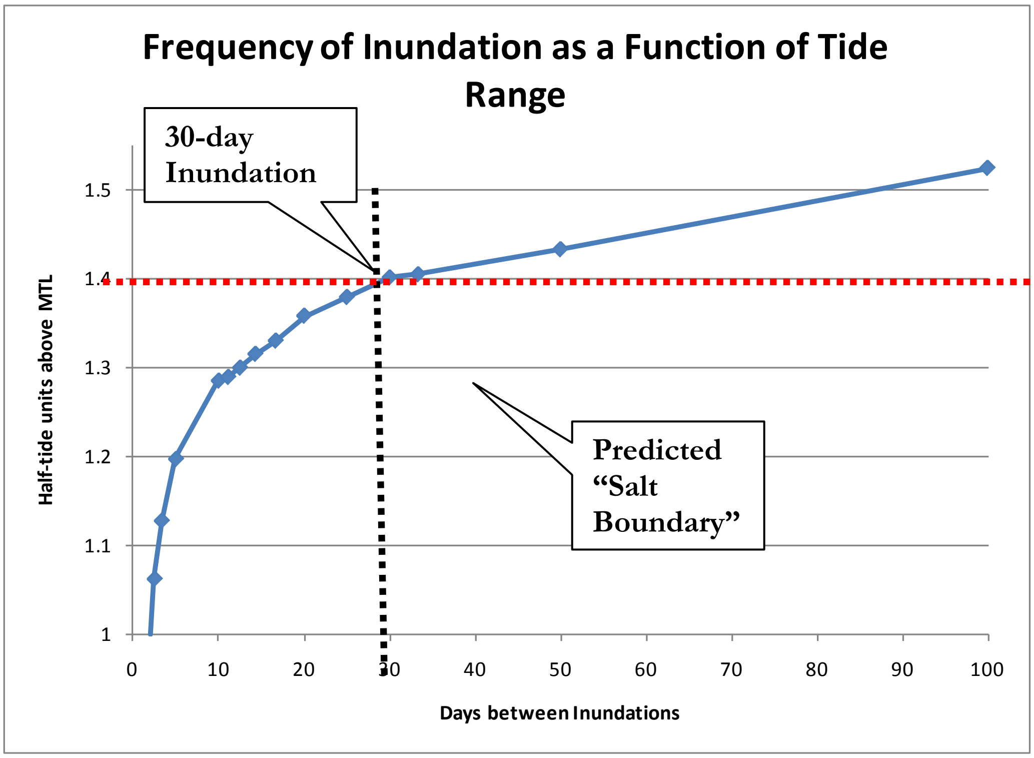


Figure 5: Frequency of inundation a function of tidal range based on 2006-2009 data from Aberdeen, WA (9441187).

According to the National Wetland Inventory, there are no impounded or diked areas within Grays Harbor NWR.

The historic trend for sea level rise was estimated at 2.0 mm/year using the value of the tide station at Seattle (9447130), This measured rate is similar to the global average for the last 100 years (approximately 1.5-2.0 mm/year).

Salt marsh vertical accretion rates used for this site were from a local accretion study which included samples taken in Elk River in southern Grays Harbor (Thom, 1992). Measured Elk River accretion rates for non-diked, mid-marshes was 6.6 mm/year, a value which was applied to regularly flooded (salt) marsh. Model accretion rates for irregularly flooded (brackish) marsh were set to 3.7 mm/year and the tidal fresh marsh to 4 mm/year. These values fall within the range of Pacific Northwest accretion measurements by Thom (1992). These rates also fall near the average values of a comprehensive literature review of accretion rates (Cahoon et al., 1995 and 1999).

Erosion rates for the tidal flat were set to 0.2 meters/year, roughly based on a regional map of shoreline erosion (Keuler, 1988). Erosion rates for marshes and swamps were set to SLAMM defaults of 2 meters/year and 1 meter/year, respectively. Horizontal erosion of marshes and swamps occurs only at the wetland-to-open-water interface and only when adequate open water (fetch) exists for wave setup.

Elevation data were converted to a mean tide level (MTL) basis using data available from NOAA tide gages and the NOAA VDATUM software. MTL to NAVD88 elevation corrections were made on a sub-site basis, as shown in Table 1 and Figure 6.

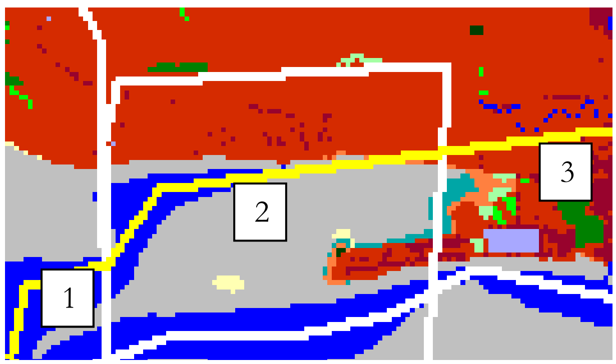


Figure 6: Grays Harbor Input subsites.

Table 1. SUMMARY OF SLAMM INPUT PARAMETERS FOR GRAYS HARBOR NWR

Parameter	SubSite 1	SubSite 2	SubSite 3
Description	Grays Harbor 1.17	Grays Harbor 1.2	Grays Harbor
NWI Photo Date (YYYY)	1981	1981	1981
DEM Date (YYYY)	1999	1999	1999
Direction Offshore [n,s,e,w]	West	West	West
Historic Trend (mm/yr)	2	2	2
MTL-NAVD88 (m)	1.17	1.2	1.16
GT Great Diurnal Tide Range (m)	2.84	3.1	3.1
Salt Elev. (m above MTL)	1.99	2.17	2.17
Marsh Erosion (horz. m /yr)	2	2	2
Swamp Erosion (horz. m /yr)	1	1	1
T.Flat Erosion (horz. m /yr)	0.2	0.2	0.2
Reg. Flood Marsh Accr (mm/yr)	6.6	6.6	6.6
Irreg. Flood Marsh Accr (mm/yr)	3.7	3.7	3.7
Tidal Fresh Marsh Accr (mm/yr)	4	4	4
Beach Sed. Rate (mm/yr)	1	1	1
Freq. Overwash (years)	0	0	0
Use Elev Pre-processor	TRUE	TRUE	TRUE

Results

Table 2 shows land cover losses predicted by this SLAMM analysis of Grays Harbor NWR. The majority of the refuge, approximately 65%, is composed of tidal flat, which is predicted to be impacted by varying degrees depending on the SLR scenario. At the lowest SLR scenario considered, 25% of the tidal flat is predicted to be lost to inundation; while at 2 m of SLR 93% is predicted to be lost. Regularly-flooded marsh is predicted to be lost in the 0.39 m and 2 m of SLR by 2100 scenarios, while in the "intermediate" scenarios this marsh is predicted to increase. This result is a consequence of regular inundation and subsequent conversion of the irregularly-flooded marsh in the refuge, which SLAMM predicts to be lost at scenarios of 0.69 m of SLR by 2100 and above.

Although it comprises only a small portion of the refuge, the inland fresh marsh is a notable category as it is predicted to be completely resilient to SLR. However, tidal fresh marsh is predicted to undergo considerable losses at 1 m SLR by 2100 and higher.

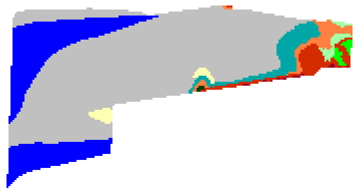
Table 2. Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise. *Positive values indicate losses and negative values indicate gains.*

Land cover category	Land cover change by 2100 for different SLR scenarios (%)				
	0.39 m	**0.69 m**	**1 m**	**1.5 m**	**2 m**
Tidal Flat	25	48	66	91	93
Regularly Flooded Marsh	1	-10	-14	-12	32
Undeveloped Dry Land	2	4	4	4	4
Irregularly Flooded Marsh	-1	14	37	82	97
Estuarine Beach	7	17	28	43	58
Tidal Fresh Marsh	0	11	29	56	86
Inland Fresh Marsh	0	0	0	0	0
Developed Dry Land	3	3	4	5	5
Tidal Swamp	20	42	61	88	100

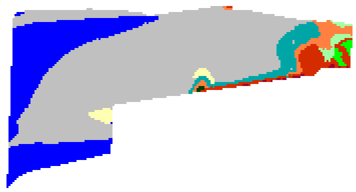
Grays Harbor NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

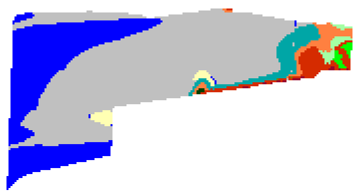
		Initial	2025	2050	2075	2100
	Tidal Flat	1210	1153	1083	996	910
	Estuarine Open Water	375	433	503	591	677
	Regularly Flooded Marsh	87	86	86	86	86
	Undeveloped Dry Land	67	67	66	66	66
	Irregularly Flooded Marsh	49	49	49	49	50
	Estuarine Beach	23	23	23	22	22
	Tidal Fresh Marsh	19	19	19	19	19
	Inland Fresh Marsh	12	12	12	12	12
	Developed Dry Land	5	5	5	5	5
	Tidal Swamp	2	2	2	2	2
	Transitional Salt Marsh	0	0	1	1	1
	Total (incl. water)	**1849**	**1849**	**1849**	**1849**	**1849**



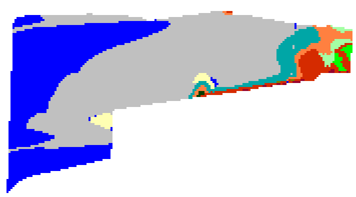
Grays Harbor NWR, Initial Condition



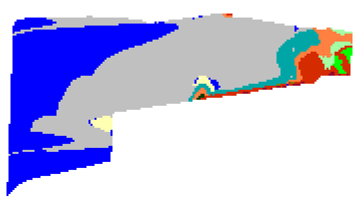
Grays Harbor NWR, 2025, Scenario A1B Mean



Grays Harbor NWR, 2050, Scenario A1B Mean



Grays Harbor NWR, 2075, Scenario A1B Mean

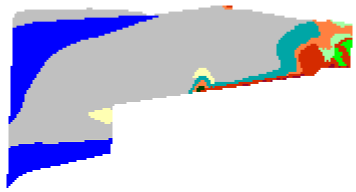


Grays Harbor NWR, 2100, Scenario A1B Mean

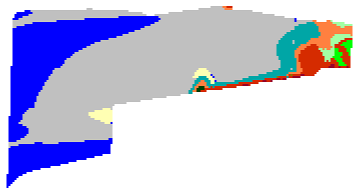
Grays Harbor NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

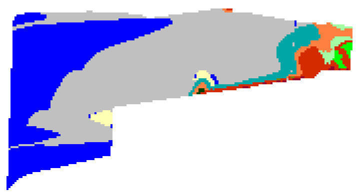
		Initial	2025	2050	2075	2100
	Tidal Flat	1210	1103	974	797	625
	Estuarine Open Water	375	483	612	791	964
	Regularly Flooded Marsh	87	86	87	91	96
	Undeveloped Dry Land	67	67	66	65	65
	Irregularly Flooded Marsh	49	49	49	46	42
	Estuarine Beach	23	23	22	21	19
	Tidal Fresh Marsh	19	19	19	18	17
	Inland Fresh Marsh	12	12	12	12	12
	Developed Dry Land	5	5	5	5	5
	Tidal Swamp	2	2	2	1	1
	Transitional Salt Marsh	0	1	1	2	2
	Total (incl. water)	**1849**	**1849**	**1849**	**1849**	**1849**



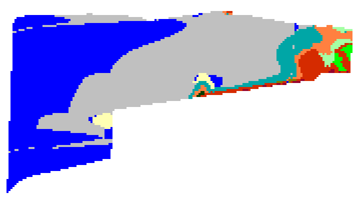
Grays Harbor NWR, Initial Condition



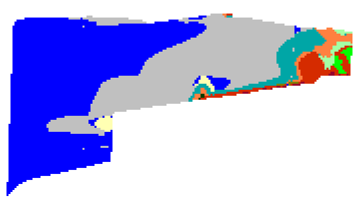
Grays Harbor NWR, 2025, Scenario A1B Maximum



Grays Harbor NWR, 2050, Scenario A1B Maximum



Grays Harbor NWR, 2075, Scenario A1B Maximum

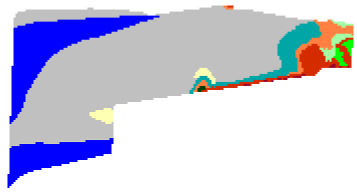


Grays Harbor NWR, 2100, Scenario A1B Maximum

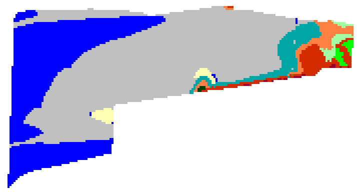
Grays Harbor NWR
1 m eustatic SLR by 2100

Results in Acres

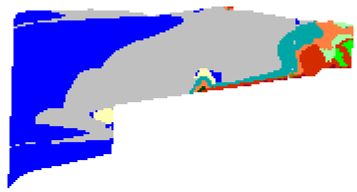
		Initial	2025	2050	2075	2100
	Tidal Flat	1210	1051	854	612	406
	Estuarine Open Water	375	535	733	982	1198
	Regularly Flooded Marsh	87	87	91	95	99
	Undeveloped Dry Land	67	66	66	65	64
	Irregularly Flooded Marsh	49	49	46	39	31
	Estuarine Beach	23	23	21	19	17
	Tidal Fresh Marsh	19	19	18	16	14
	Inland Fresh Marsh	12	12	12	12	12
	Developed Dry Land	5	5	5	5	5
	Tidal Swamp	2	2	1	1	1
	Transitional Salt Marsh	0	1	1	2	2
	Total (incl. water)	**1849**	**1849**	**1849**	**1849**	**1849**



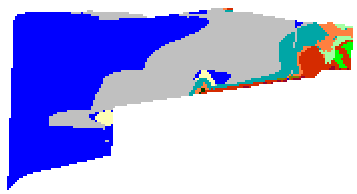
Grays Harbor NWR, Initial Condition



Grays Harbor NWR, 2025, 1 Meter



Grays Harbor NWR, 2050, 1 Meter



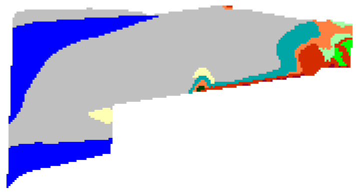
Grays Harbor NWR, 2075, 1 Meter

Grays Harbor NWR, 2100, 1 Meter

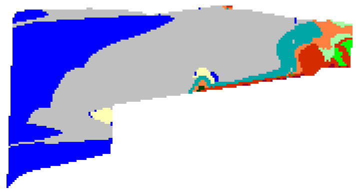
Grays Harbor NWR
1.5 m eustatic SLR by
2100

Results in Acres

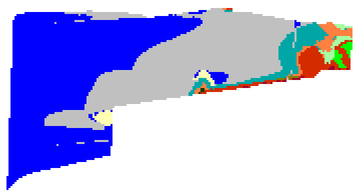
		Initial	2025	2050	2075	2100
	Tidal Flat	1210	966	672	373	106
	Estuarine Open Water	375	621	926	1243	1533
	Regularly Flooded Marsh	87	89	92	96	97
	Undeveloped Dry Land	67	66	65	64	64
	Irregularly Flooded Marsh	49	47	39	24	9
	Estuarine Beach	23	22	20	16	13
	Tidal Fresh Marsh	19	19	16	12	8
	Inland Fresh Marsh	12	12	12	12	12
	Developed Dry Land	5	5	5	5	5
	Tidal Swamp	2	2	1	1	0
	Transitional Salt Marsh	0	1	2	2	0
	Total (incl. water)	**1849**	**1849**	**1849**	**1849**	**1849**



Grays Harbor NWR, Initial Condition

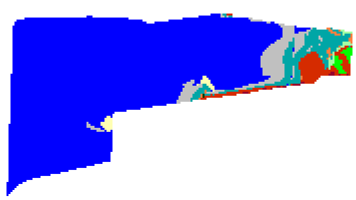


Grays Harbor NWR, 2025, 1.5 Meters



Grays Harbor NWR, 2050, 1.5 Meters

Grays Harbor NWR, 2075, 1.5 Meters

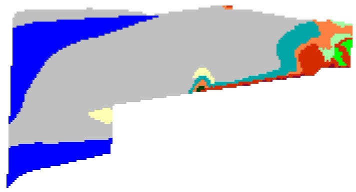


Grays Harbor NWR, 2100, 1.5 Meters

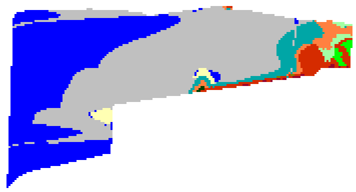
Grays Harbor NWR
2 m eustatic SLR by 2100

Results in Acres

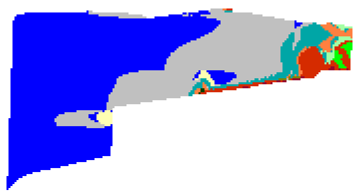
		Initial	2025	2050	2075	2100
	Tidal Flat	1210	881	522	163	90
	Estuarine Open Water	375	710	1089	1480	1605
	Regularly Flooded Marsh	87	89	93	92	59
	Undeveloped Dry Land	67	66	64	64	64
	Irregularly Flooded Marsh	49	44	29	10	1
	Estuarine Beach	23	21	18	14	10
	Tidal Fresh Marsh	19	18	14	9	3
	Inland Fresh Marsh	12	12	12	12	12
	Developed Dry Land	5	5	5	5	5
	Tidal Swamp	2	2	1	0	0
	Transitional Salt Marsh	0	1	2	1	0
	Total (incl. water)	**1849**	**1849**	**1849**	**1849**	**1849**



Grays Harbor NWR, Initial Condition

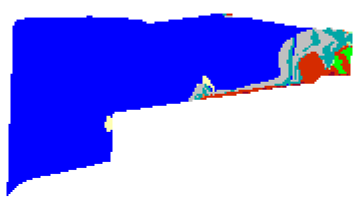


Grays Harbor NWR, 2025, 2 Meters



Grays Harbor NWR, 2050, 2 Meters

Grays Harbor NWR, 2075, 2 Meters



Grays Harbor NWR, 2100, 2 Meters

Discussion

SLAMM analysis suggests Grays Harbor NWR will be impacted by sea-level rise. The effects of SLR on tidal flat and salt marshes may be severe depending on the SLR scenario. However, inland fresh marsh is predicted to be resilient to SLR in each scenario tested.

Because it is outside of the LiDAR coverage area shown in Figure 2, results from Grays Harbor NWR are subject to significant uncertainty. The 20 foot contours used for the elevation data layer provide little-to-no information about land elevations in the intertidal zone. This SLAMM simulation worked around that problem by estimating elevation ranges as a function of tide range and known relationships between wetland types and tide ranges (using the elevation pre-processor). However, this tool assumes that wetland elevations are uniformly distributed over their feasible vertical elevation ranges or "tidal frames"—an assumption that may not reflect reality. If wetlands elevations are actually clustered high in the tidal frame they would be less vulnerable to SLR. On the contrary, if in reality wetlands are towards the bottom, they are more vulnerable than what is predicted by the simulation results.

In addition, tidal flat results are an especially uncertain portion of SLAMM model results. The effects of storms, spatially variable erosion and accretion rates, and uncertainty about the initial tidal-flat to open-water boundary make a precise accounting of tidal-flat fate difficult to achieve.

The area surrounding Grays Harbor was studied in a previous SLAMM analysis funded by Ducks Unlimited (Warren Pinnacle Consulting, Inc. 2010). Maps of results for the larger study area are presented in the "contextual maps" below.

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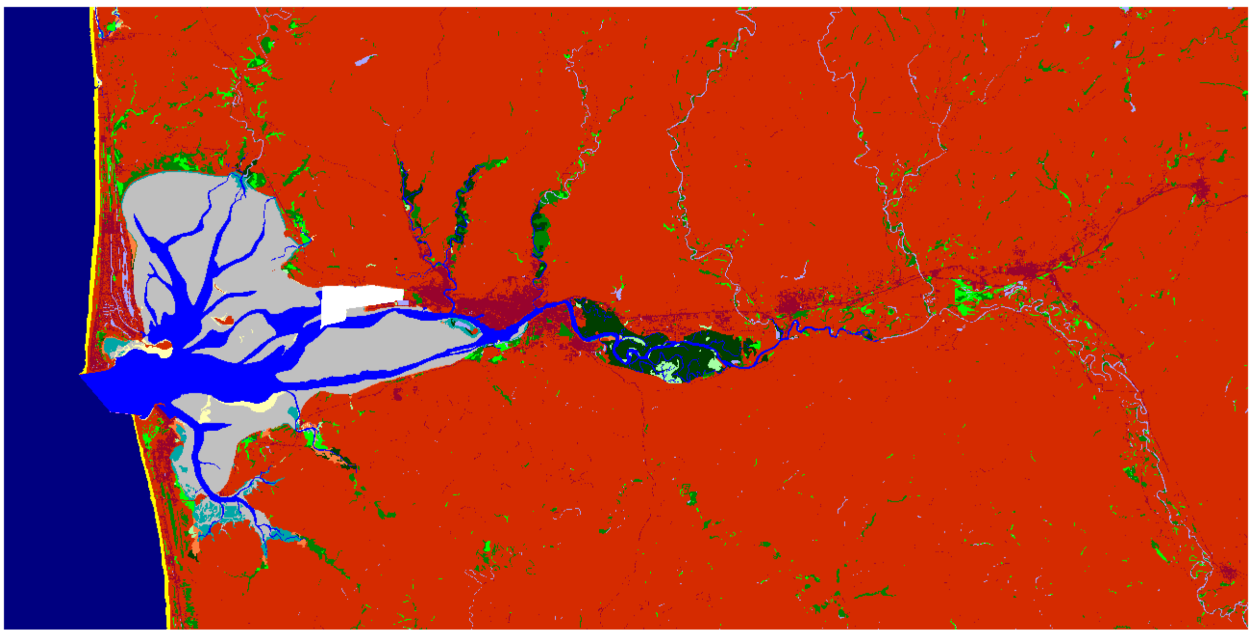
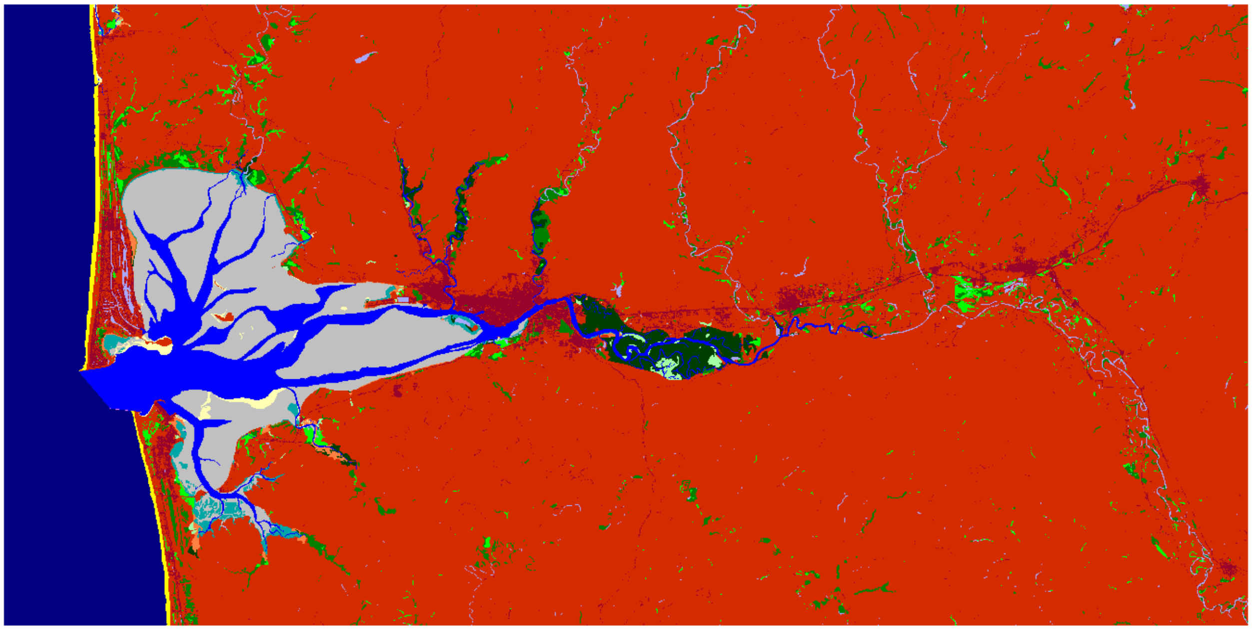
Appendix A: Contextual Results

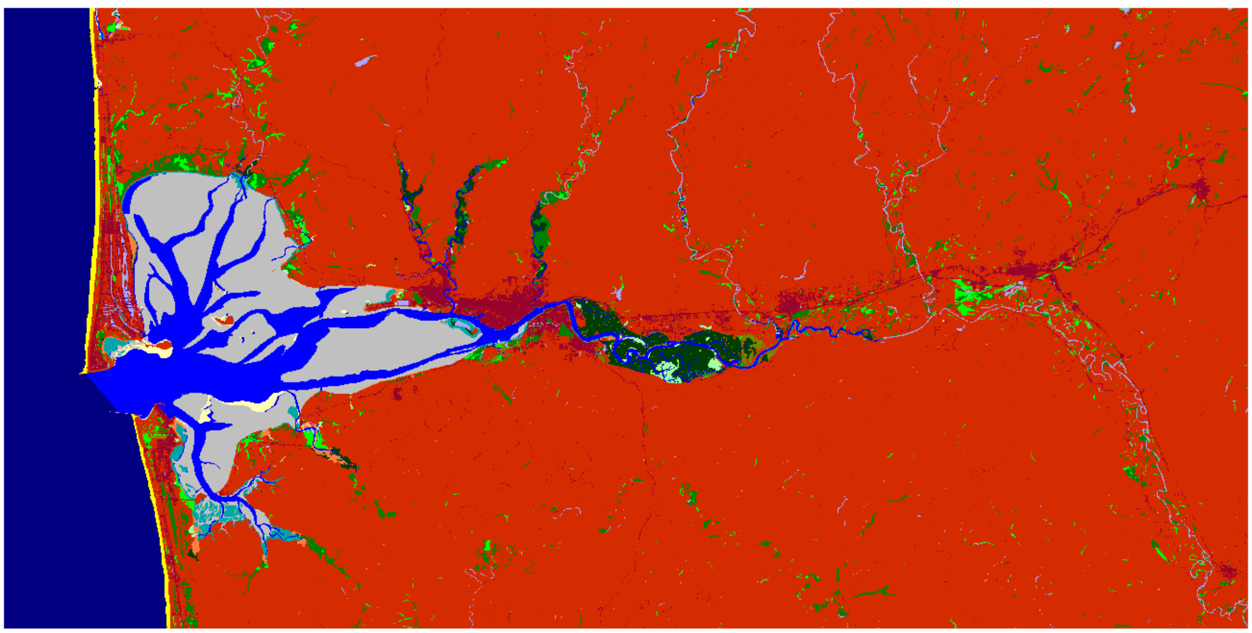
The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated dry lands will convert to marshes or ocean beach depending on their proximity to open ocean. For this reason, an area larger than the boundaries of the USFWS refuge was modeled. A full analysis of this study area was funded by Ducks Unlimited. The maps presented here reflect the results of simulations where dikes were not included.



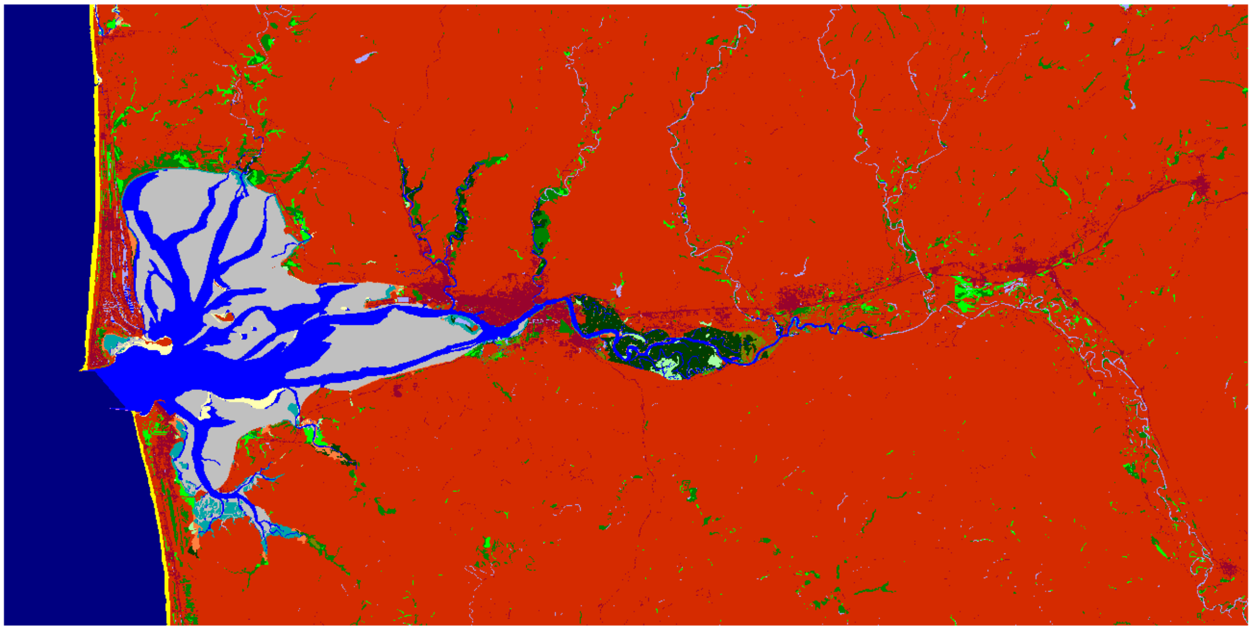
Grays Harbor National Wildlife Refuge within simulation context (in white).



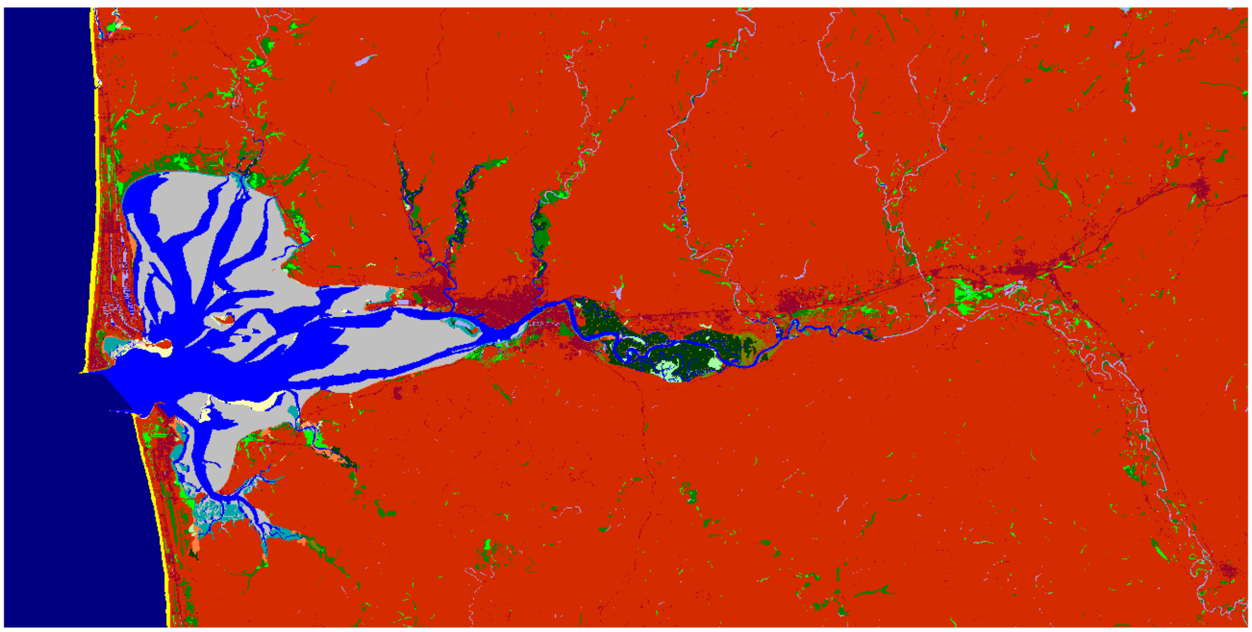
Grays Harbor Context, Initial Condition



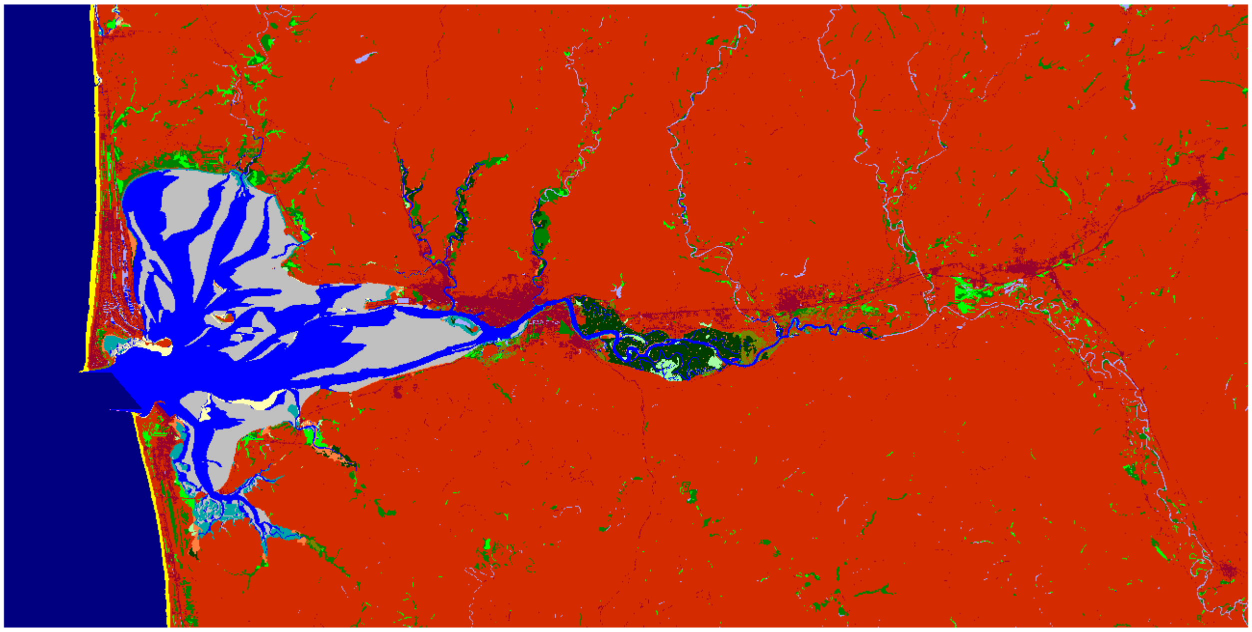
Grays Harbor Context, 2025, Scenario A1B Mean



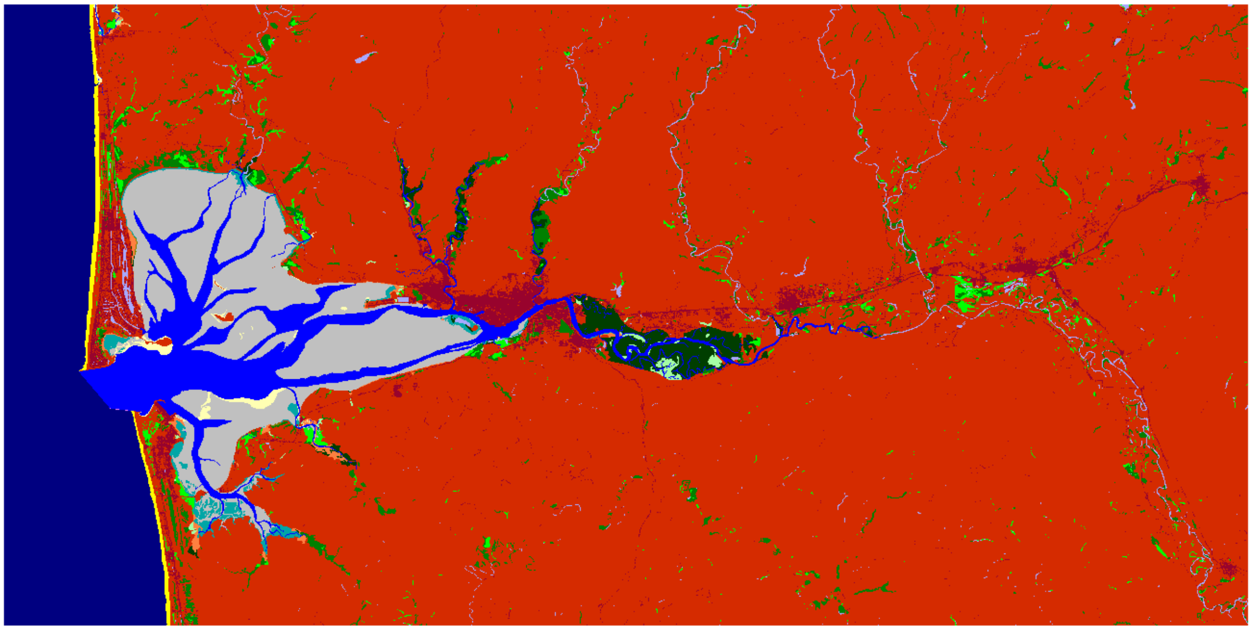
Grays Harbor Context, 2050, Scenario A1B Mean



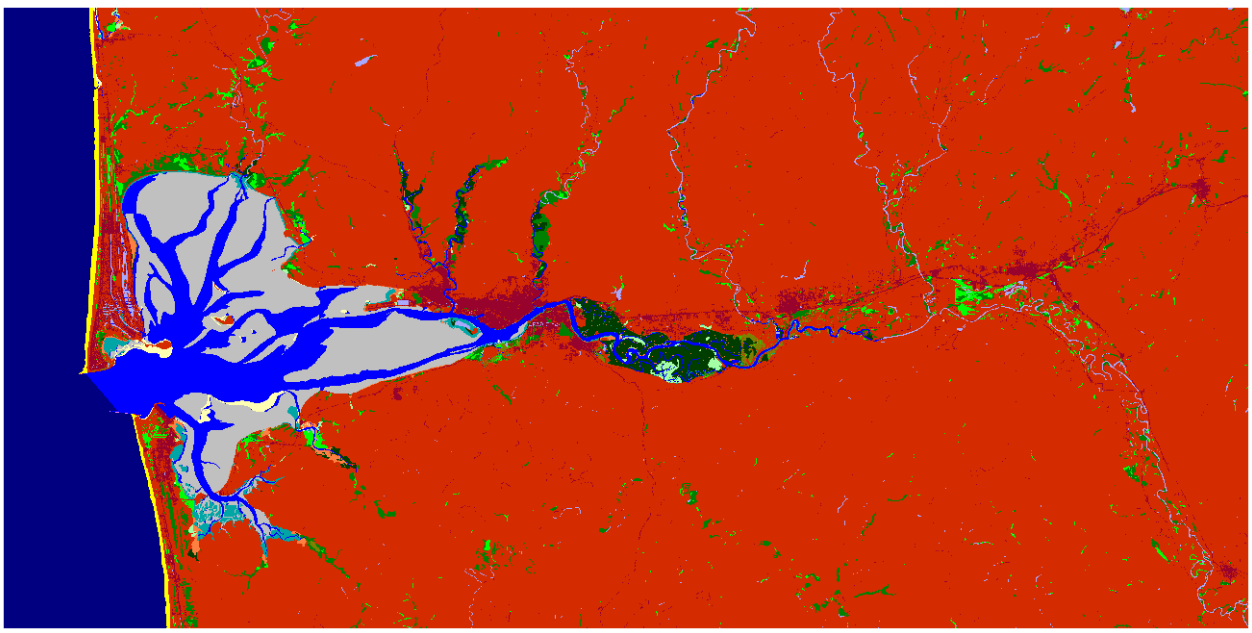
Grays Harbor Context, 2075, Scenario A1B Mean



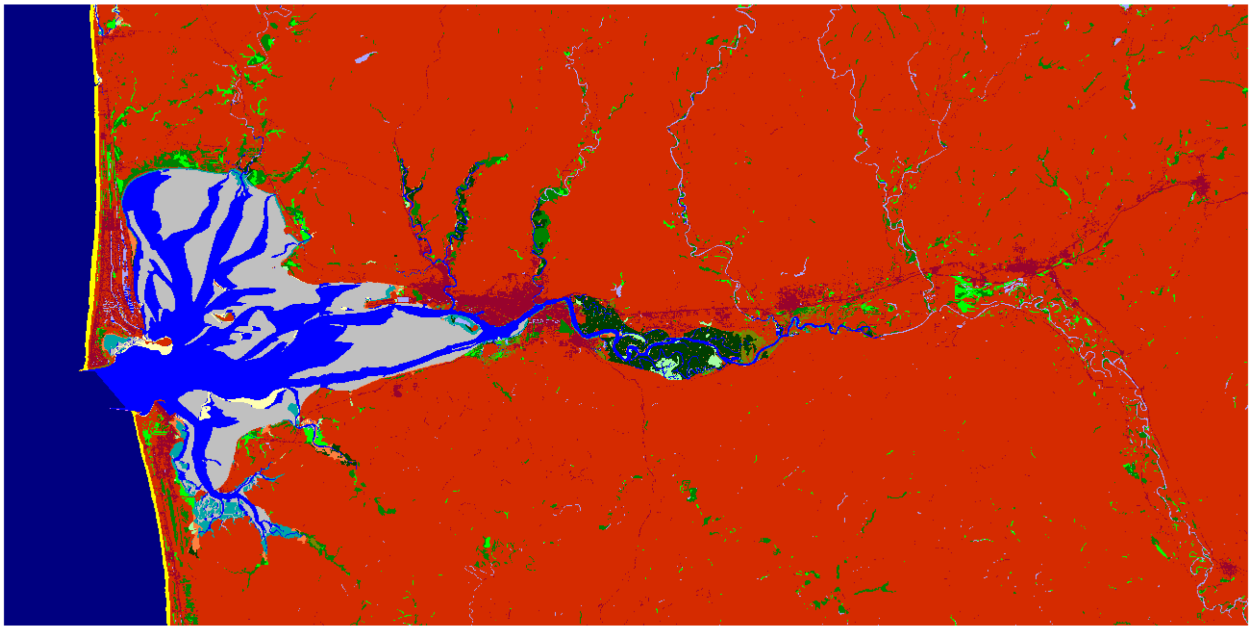
Grays Harbor Context, 2100, Scenario A1B Mean



Grays Harbor Context, Initial Condition



Grays Harbor Context, 2025, Scenario A1B Maximum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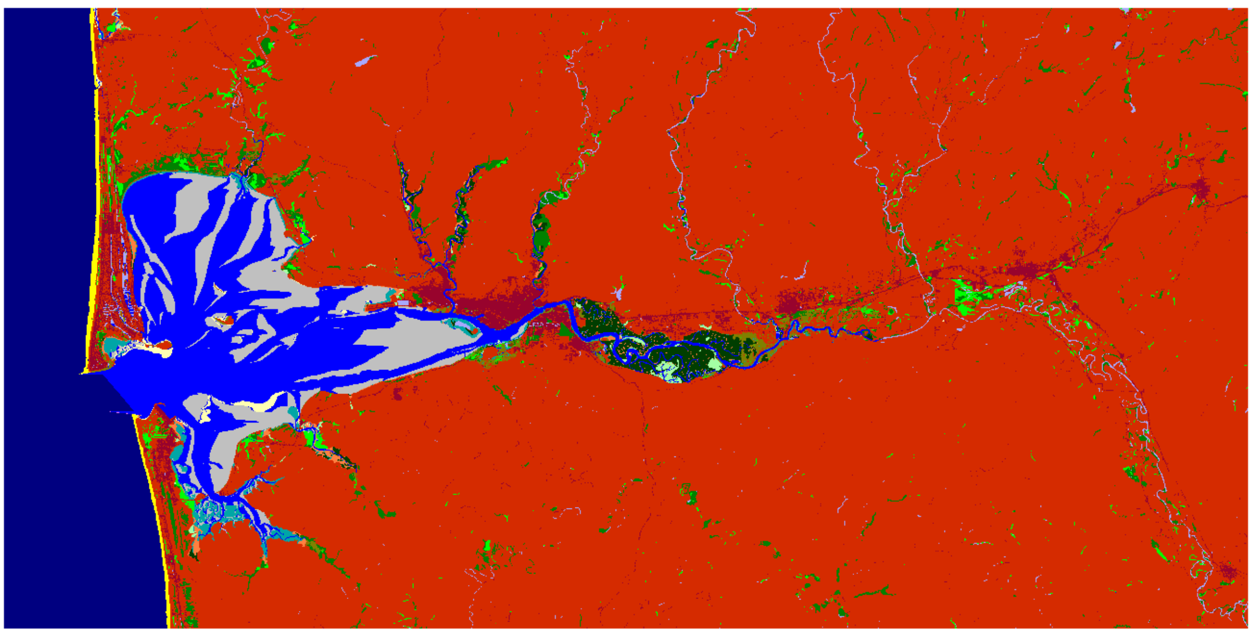
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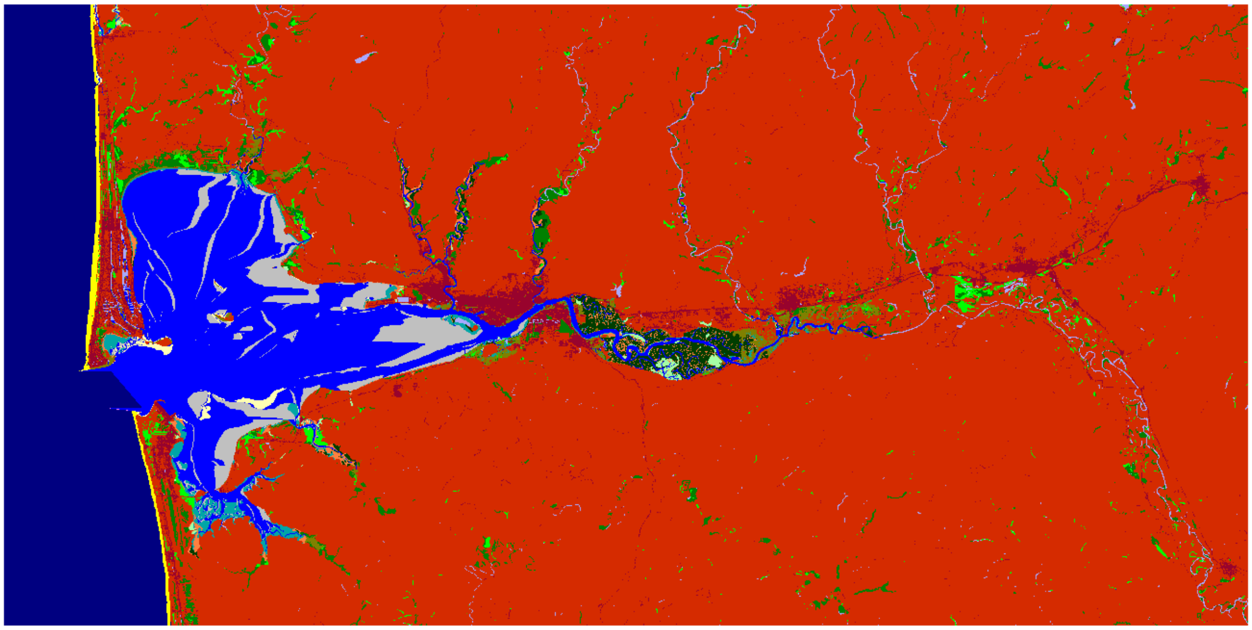
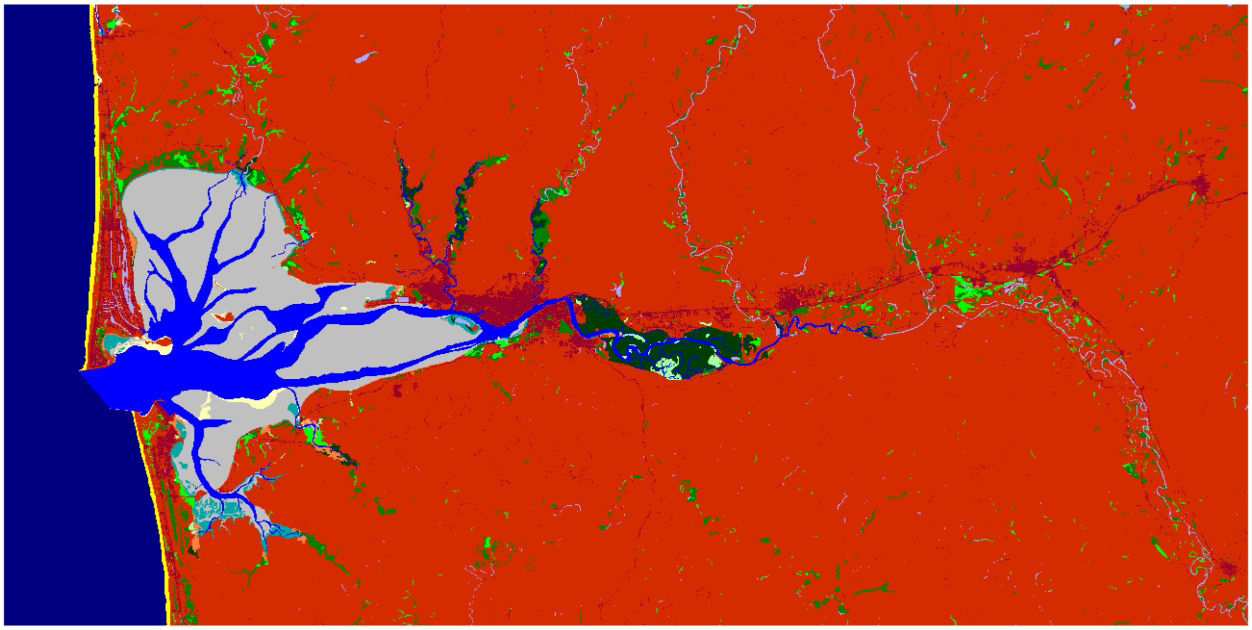
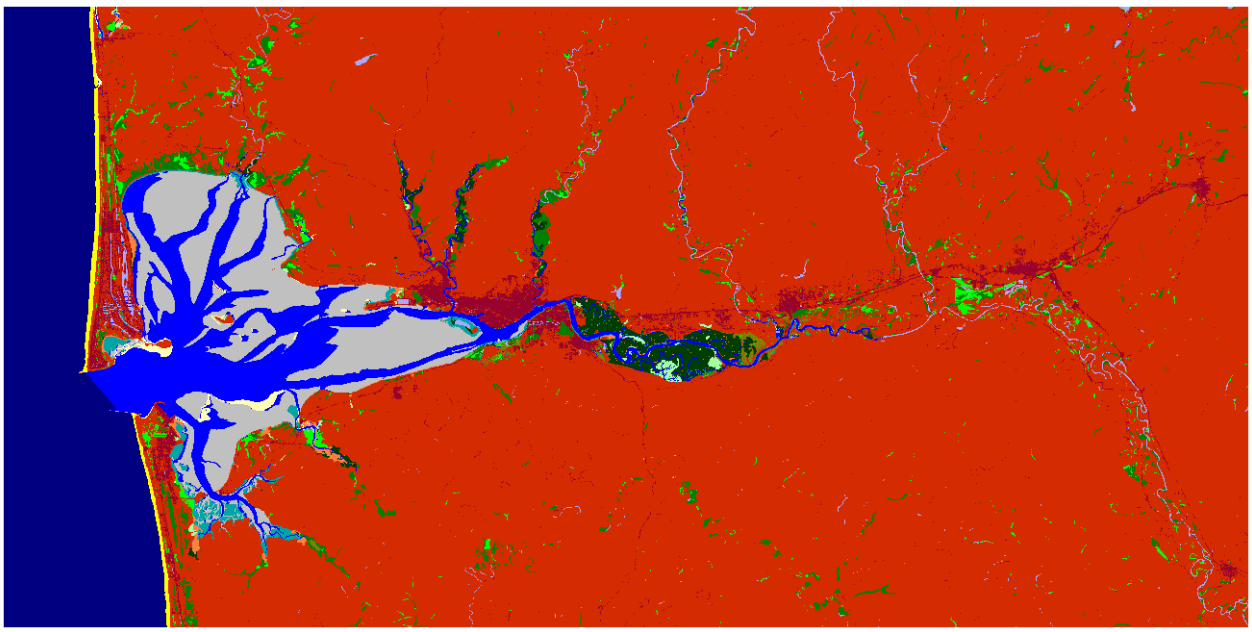


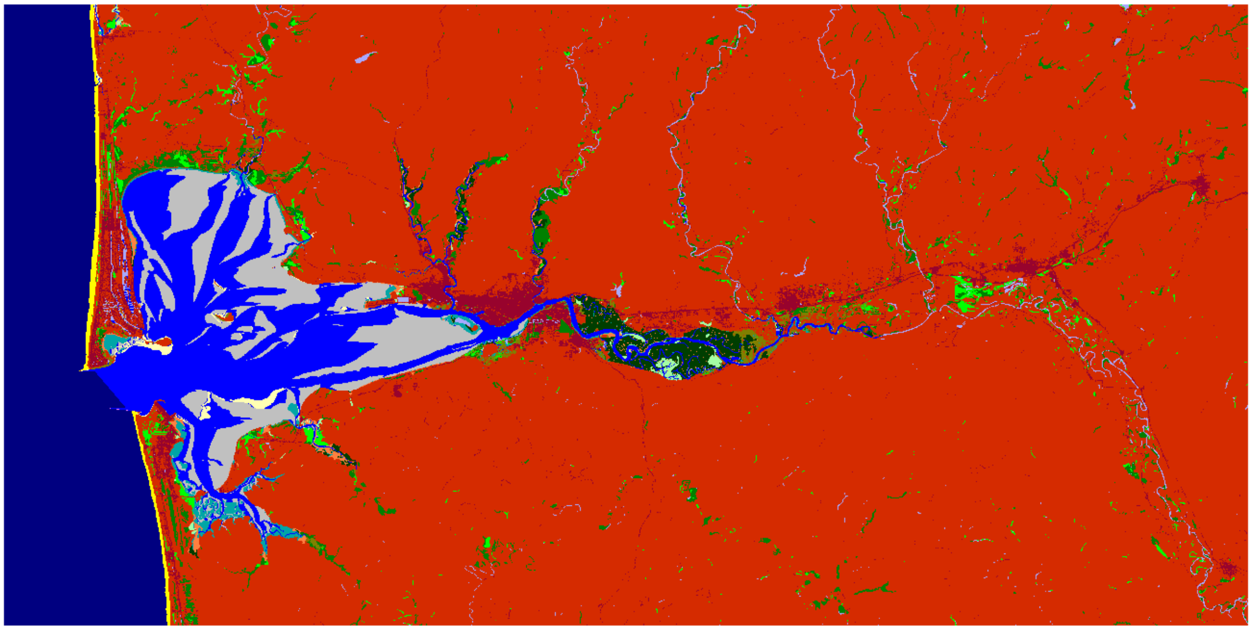
Grays Harbor Context, 2100, Scenario A1B Maximum



Grays Harbor Context, Initial Condition



Grays Harbor Context, 2025, 1 meter



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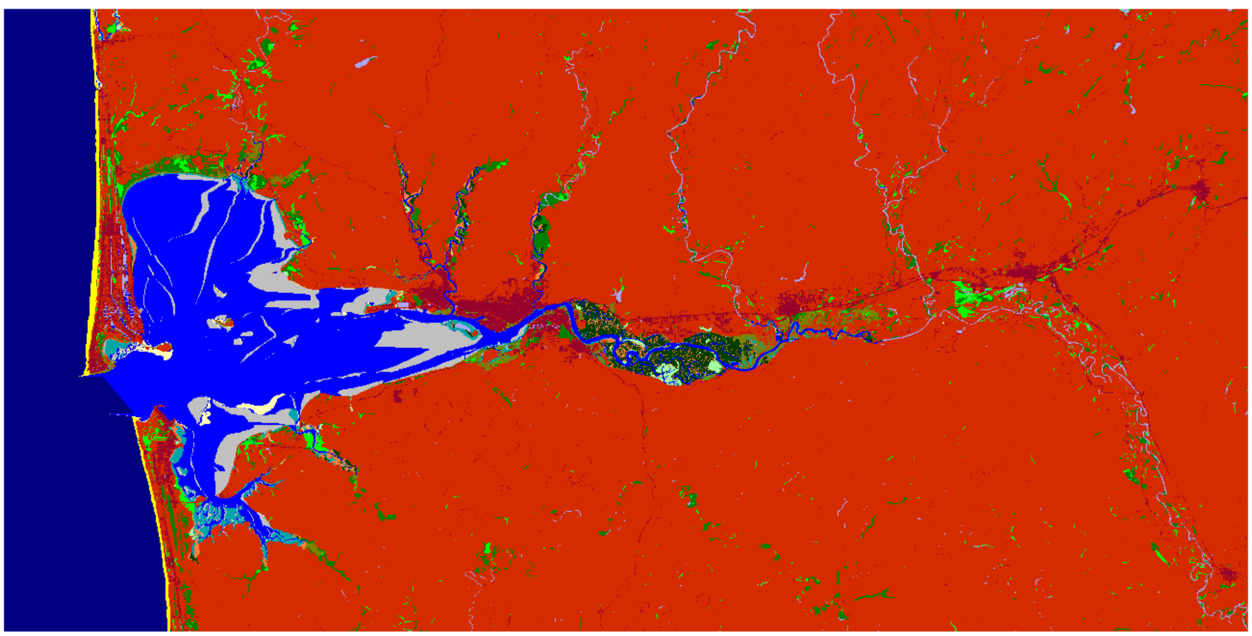
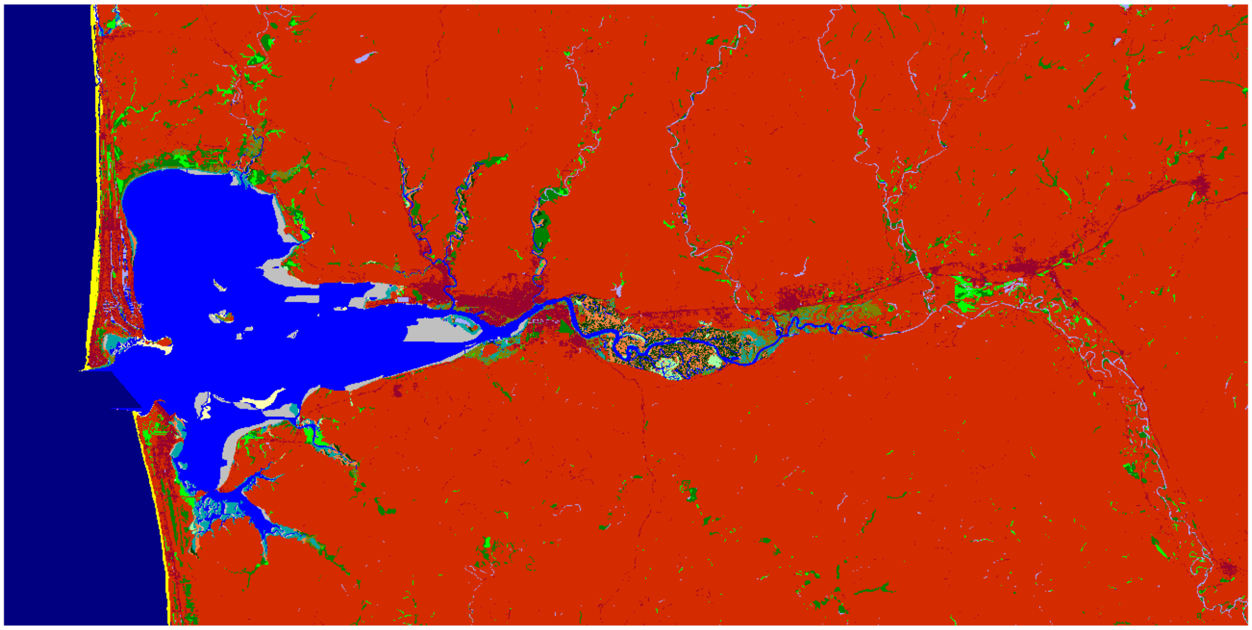
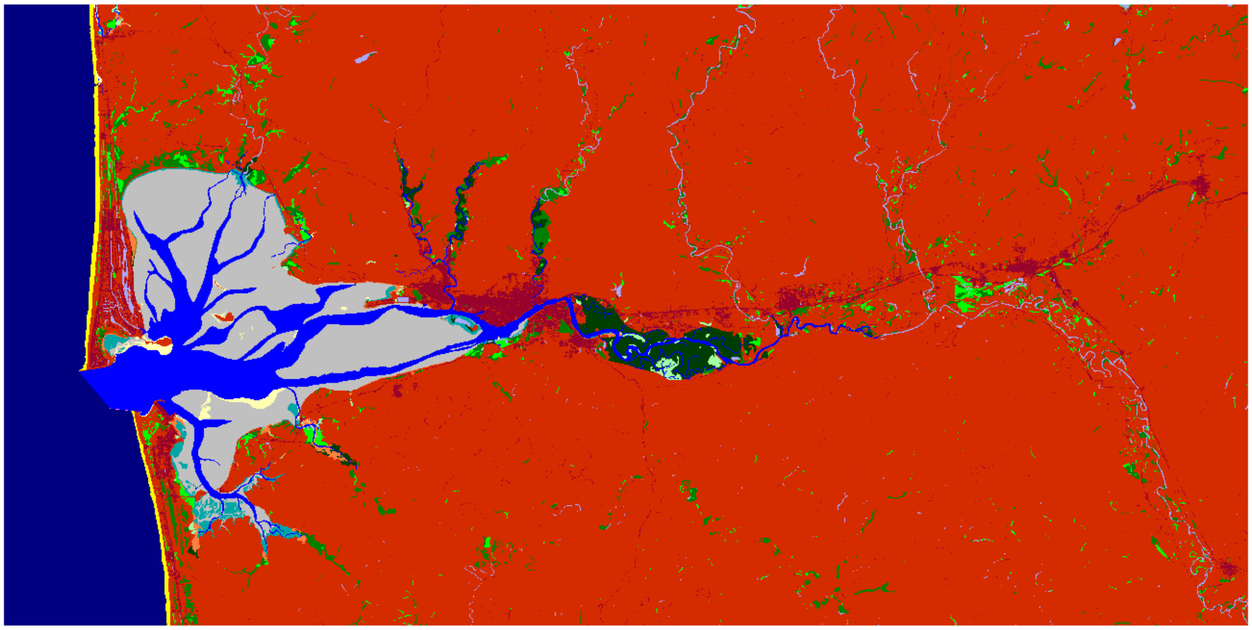
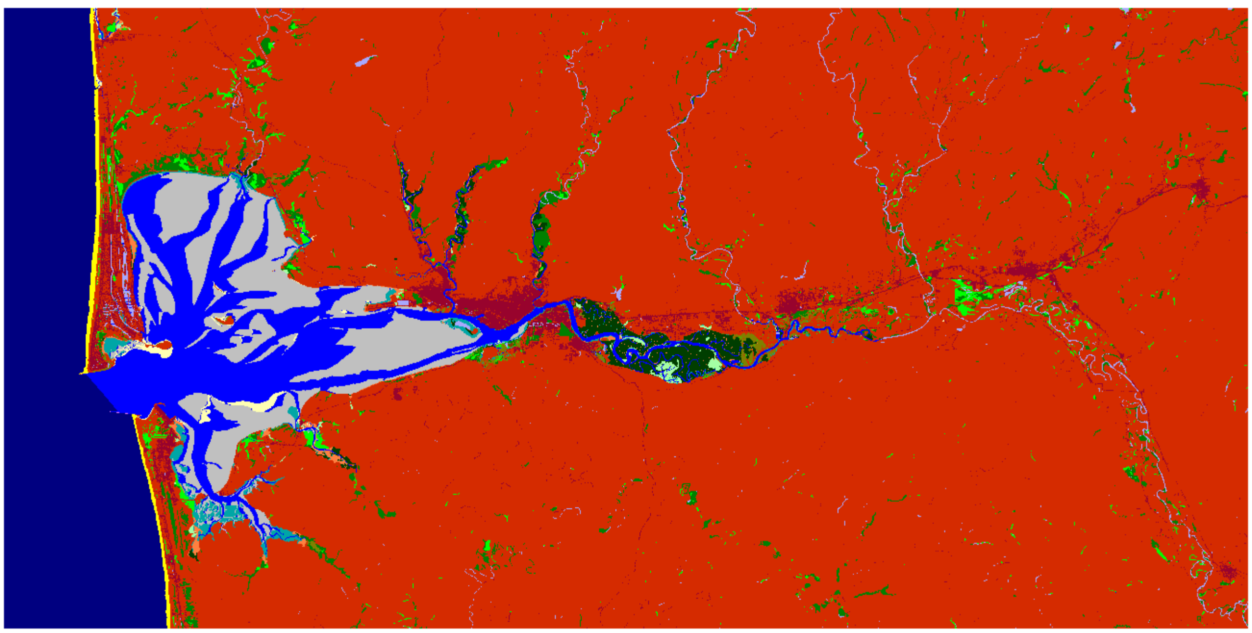


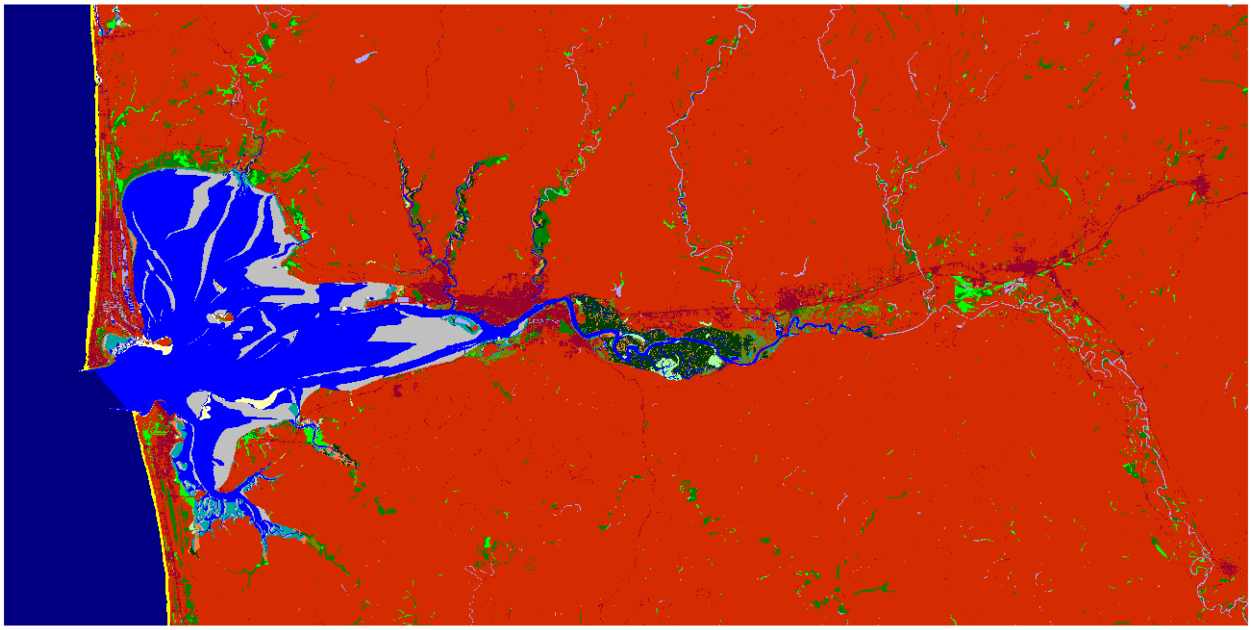
Grays Harbor Context, 2075, 1 meter



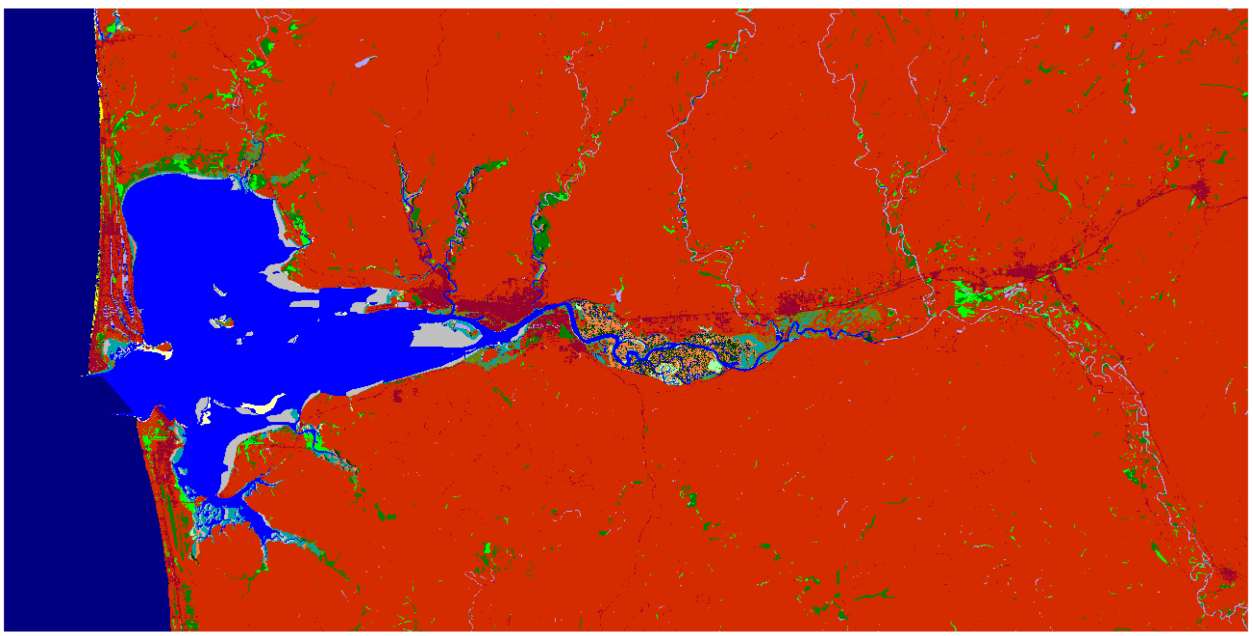
Grays Harbor Context, 2100, 1 meter


Grays Harbor Context, Initial Condition

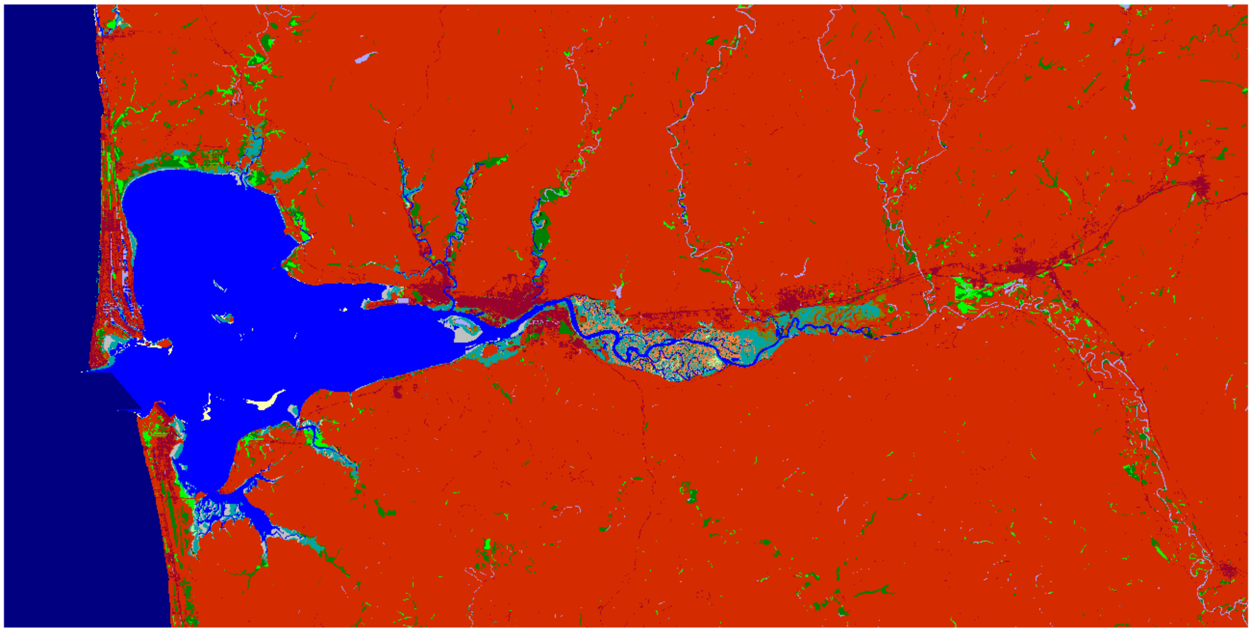

Grays Harbor Context, 2025, 1.5 meter



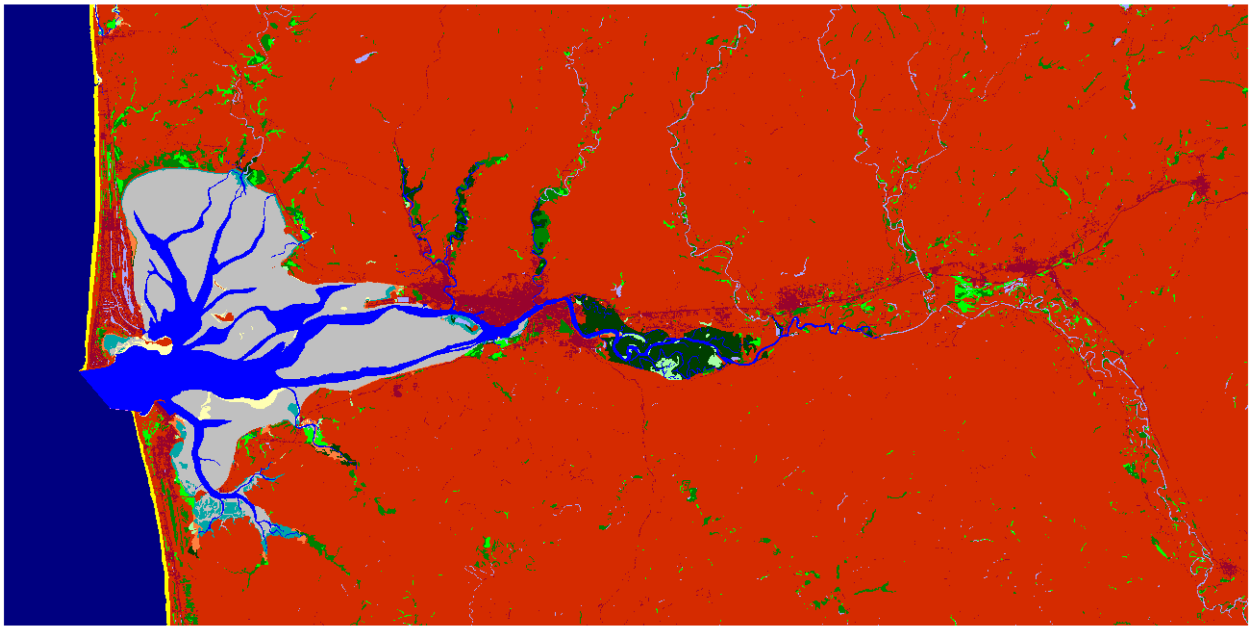
Grays Harbor Context, 2050, 1.5 meter

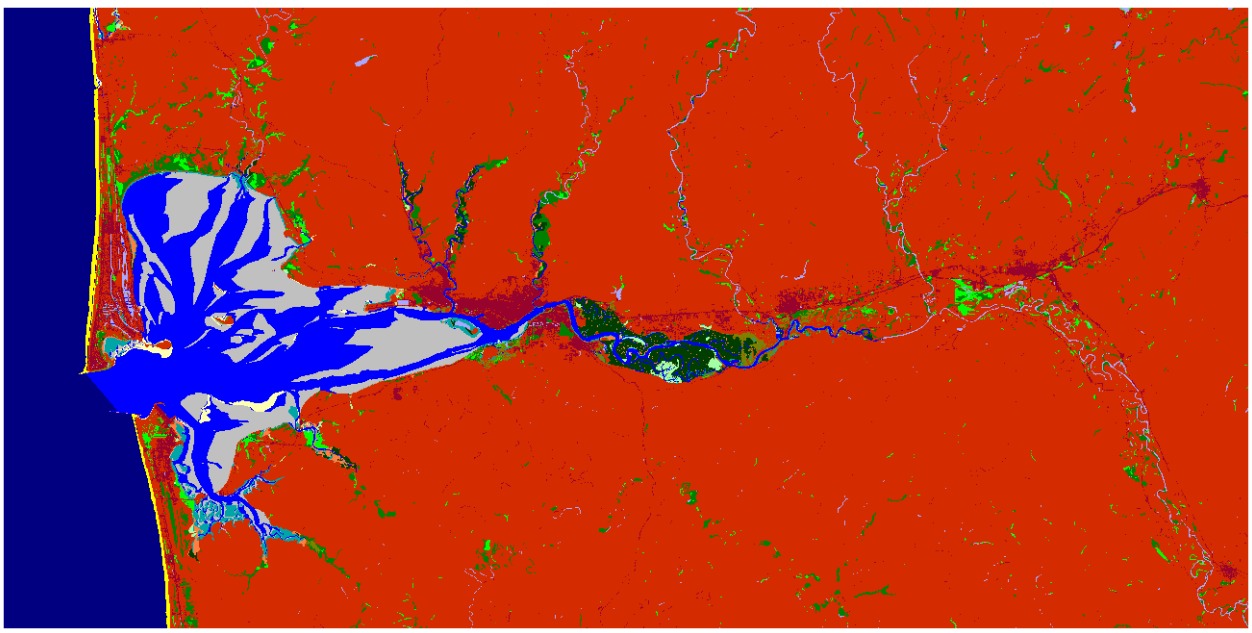


Grays Harbor Context, 2075, 1.5 meter



Grays Harbor Context, 2100, 1.5 meter


Grays Harbor Context, Initial Condition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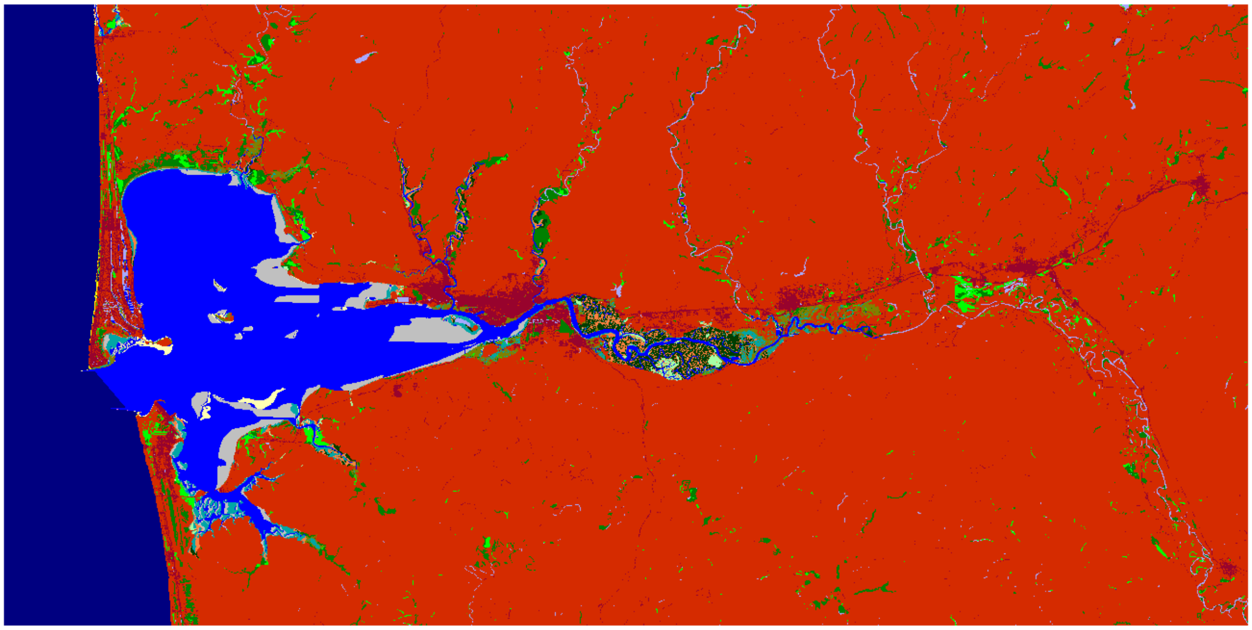

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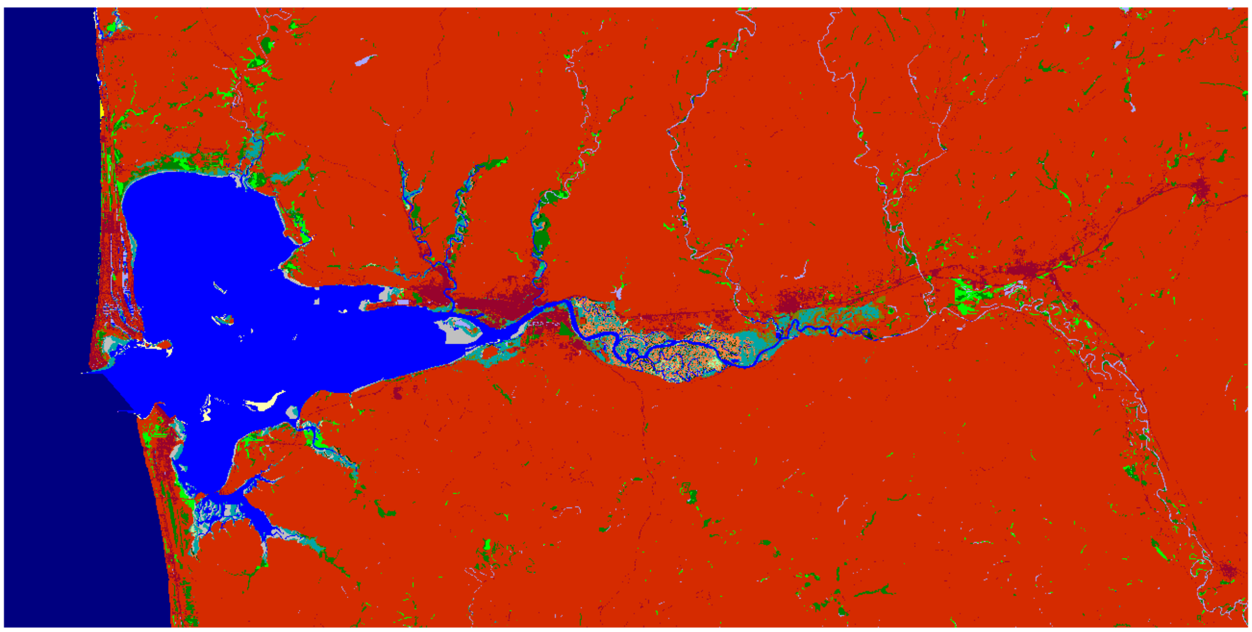
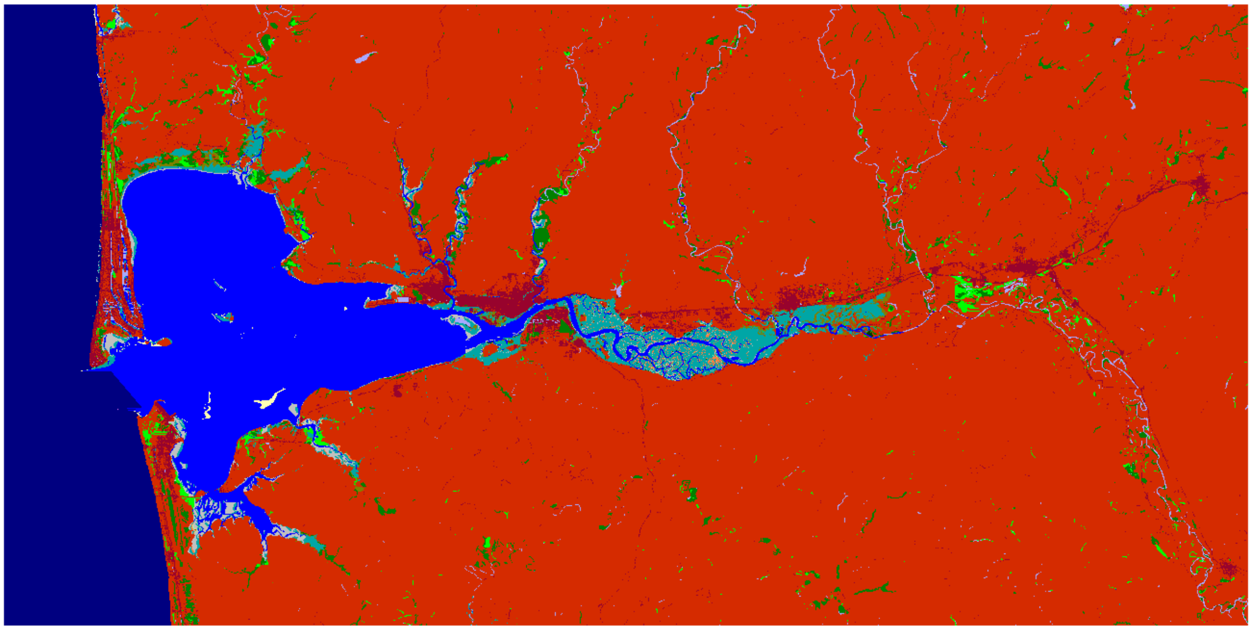


Grays Harbor Context, 2075, 2 meter



Grays Harbor Context, 2100, 2 meter